Geological Circular 84-2

Oil Accumulation, Production Characteristics, and Targets for Additional Recovery in Major Oil Reservoirs of Texas

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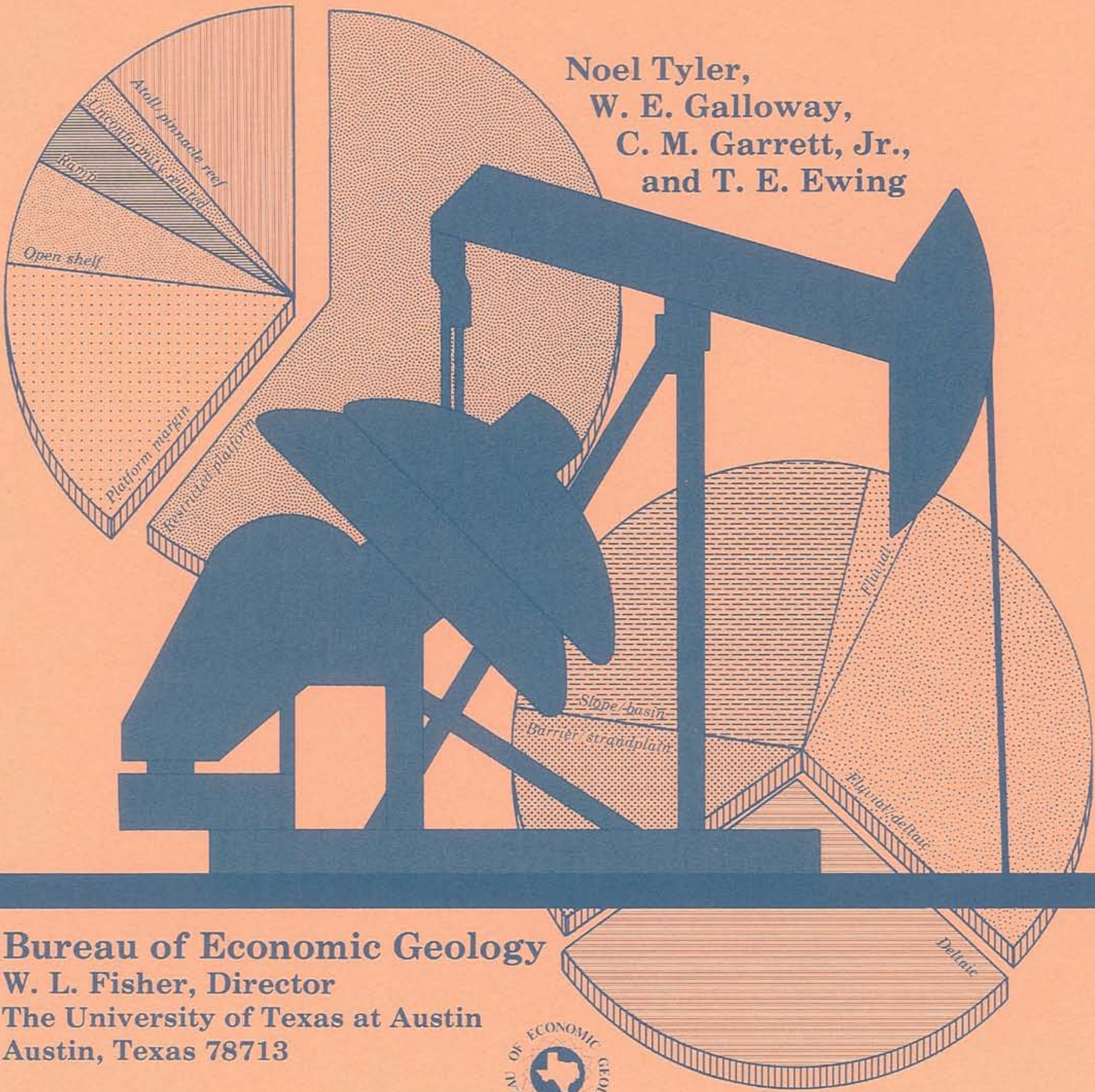

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
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OIL ACCUMULATION, PRODUCTION CHARACTERISTICS, AND TARGETS FOR ADDITIONAL RECOVERY IN MAJOR OIL RESERVOIRS OF TEXAS

by

Noel Tyler, W. E. Galloway, C. M. Garrett, Jr.,
and T. E. Ewing

assisted by W. A. Ambrose, J. S. Posey,
and M. T. Woodward III

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ABSTRACT

Characterization of 500 of the largest Texas oil reservoirs permits grouping into plays of similar geology and common engineering and production attributes. Most of the major oil reservoirs of Texas are included in 48 plays, which account for 71 percent (32 billion barrels cumulative) of all historical production in Texas. Twenty-seven oil plays lie north and west of the Marathon-Ouachita structural front in Paleozoic reservoirs that are predominantly dolomite and that contained 73 percent of the original oil in place (OOIP) in Texas. Most of the oil in these Paleozoic plays is trapped in restricted-platform and, to a lesser extent, in platform-margin and atoll/reef carbonate systems and in deep-water slope and basinal clastic systems of the Permian Basin. Recovery efficiencies of the Paleozoic plays are considerably lower than are those of the 21 Mesozoic and Cenozoic plays of the Gulf Coast and East Texas Basins. Major reservoirs in Cretaceous and Tertiary plays were deposited principally in deltaic and barrier/strandplain systems.

Reservoir genesis clearly influenced patterns of hydrocarbon accumulation and recovery. In-place oil in clastic reservoirs is distributed fairly evenly among fluvial/deltaic, deltaic, barrier/strandplain, and slope and basinal sandstones. Recoveries from clastic facies in Texas are dominated by production from deltaic reservoirs, which are projected to ultimately produce almost half (47 percent) of all oil obtained from clastic reservoirs. Slope/basin sandstones, in contrast, contained one quarter of the OOIP in clastic facies but will produce only 5 percent of the total obtained from Texas' clastic reservoirs. The statewide weighted average recovery from sandstone reservoirs is 41 percent. Weighted average recoveries by play range from a low of 8 percent from slope/basin systems to a high of 68 percent from deltaic plays.

Original in-place oil is less uniformly distributed among carbonate reservoir facies than among clastic reservoir facies. Restricted-platform plays trapped 61 percent of the OOIP in carbonate reservoirs, whereas platform-margin and deep-water carbonate reservoirs held 16 and 11 percent, respectively. Oil recovery from restricted-platform carbonates is relatively poor; only 30 percent of the original resource will be produced by primary or secondary methods from these plays. Deep-water atoll and pinnacle-reef reservoirs exhibit the best recoveries (50 percent), largely because of successful secondary recovery programs begun early in field development.

The potential target for additional oil recovery from major Texas reservoirs in which depositional or diagenetic complexity significantly limits recovery is 20 billion barrels. Most of this target oil is trapped in restricted-platform carbonates and slope/basin sandstones of the Permian Basin.

Keywords: Texas, major oil reservoirs, oil accumulation trends, oil recovery, targets for additional oil recovery, oil plays.

INTRODUCTION

Texas is the greatest petroleum province of the United States. In the 83 years following the spectacular completion of the Lucas well at Spindletop salt dome east of Houston in 1901, 11,340 oil fields have been discovered in Texas. These fields have produced 46 billion barrels of oil, accounting for nearly 40 percent of the historic production of crude oil in the United States (Fisher and Galloway, 1983). Eight of the 20 largest oil fields in the United States lie within Texas (based on remaining proved reserves of crude oil on December 31, 1979; American Gas Association and others, 1980). This is more than any other state; California ranks second with 6 of the 20 largest oil fields. Crude oil and condensate produced from Texas fields in 1982 amounted to 872 million barrels (Railroad Commission of Texas, 1983). Texas fields contain 55 giant oil reservoirs that, by definition, have each produced more than 100 million barrels of oil. The biggest of these is the East Texas field, which ranks number one nationally in cumulative production and reservoir performance. East Texas field alone had produced 4.7 billion barrels of oil by the end of 1982 (Railroad Commission of Texas, 1983), and estimated ultimate recovery is 80 percent (Galloway and others, 1982).

Recovery of oil from the major Texas reservoirs included in this survey averages 37 percent. A current estimate of ultimate statewide recovery is 54 billion barrels of the 156 billion barrels of oil discovered in Texas (Fisher and Galloway, 1983). Thus, of the known oil resource in Texas, more than 100 billion barrels is now classed as unrecoverable by conventional means.

As part of a broad research program aimed at investigating the potential for additional recovery from Texas oil fields, the Bureau of Economic Geology undertook in 1982 and 1983 a survey of the 500 most productive oil reservoirs in the state. Only those reservoirs that had produced more than 10 million barrels of oil by the end of 1981 were included in the study. Thirty parameters that collectively characterize geological, engineering, and production attributes were compiled for each reservoir. These data include (1) general reservoir information such as location, discovery date, and trap style, (2) matrix and fluid properties, (3) engineering characteristics and technology employed in reservoir management, and (4) oil volumetrics. Reservoirs were then grouped into plays on the basis of similar geology and petrophysical character (White, 1980). An example of the data tabulation used to define plays is illustrated in table 1.

Reservoir origin is the most important parameter in play definition. Trap style and the nature of the available source rocks and seals are also considered. Most of the major oil reservoirs in Texas are grouped into 48 plays (fig. 1), which account for 71 percent (32 billion barrels) of all oil produced in Texas. This study therefore analyzes a representative sample of Texas oil reservoirs; the conclusions reached concerning the geologic controls on oil accumulation and production trends are applicable to all Texas oil fields.

Table 1. Representative table showing data compiled to characterize major Texas oil reservoirs. Data shown here are for the Spraberry-Dean sandstone play.

RRC DIST.	FIELD AND RESERVOIR	DISC. DATE	LITH-OLOGY	TRAP	DRIVE	DEPTH (FT)	OIL COL. (FT)	POR. (%)	PERMEABILITY AVG. (MD)	PERMEABILITY LOG RANGE	H2O SAT.	API GRAV.	INIT. GOR	INIT. PRES.	TEMP. (F)	PRODUCTION TECHNOLOGY	UNIT. DATE	WELL SPACING (ACRES)	ROS (%)	OIP (MMBBL)	CUM. PROD. (MMBBL)	ULT. RECOV. (MMBBL)	REC. EFF. (%)
8A	ACKERLY DEAN	54	SS	UPP	SG	8200	500	10	0	-1 0	40	38	985	3660	138	WF	69-76	80		250	30.3	34.6	14
7C	BENEDUM SPRABERRY	47	SS	PPS	SG	7600	250	12	1	-1 0	35	36	538	2315		WF	67	100		200	22.0	30.0	15
7C	CALVIN DEAN	65	SS	UPP	SG	7400		11	1	-1 0	35	41	4000	2484	141			160	50	270	28.3	35.0	13
7C	COPE	51	SS	I	SG	5100		16	24	-1 2	20	35	450	1950		WF	59	40	47	31	11.6	12.0	39
8A	JO-MILL SPRABERRY	54	SS	UPP	SG	7100		16	3		39	39	800	2843	109	WF,PMW	63-69	80	44	330	54.7	79.0	24
7C	PEGASUS SPRABERRY	52	SS	SA	SG	8300	160	8	0		35	37	600	2675	135	WF	63	80-160	46	100	11.4	12.7	13
7C	SPRABERRY TREND	49	SS	UPP	SG	6800		10	0	-1 0	35	39	613	2500	132	WF,PMW	62-65	80	28	9400	457.0	470.0	5
						6948	353	11	1		35	39	798	2573	131		86 %		31	10581	615.3	673.3	6

SS - sandstone. *Trap mechanism:* **I** - isolani; **PPS** - partly productive structure; **SA** - simple anticline or dome; **UPP** - updip porosity pinch-out. *Production technology:* **PMW** - pressure maintenance by water injection; **WF** - waterflood.

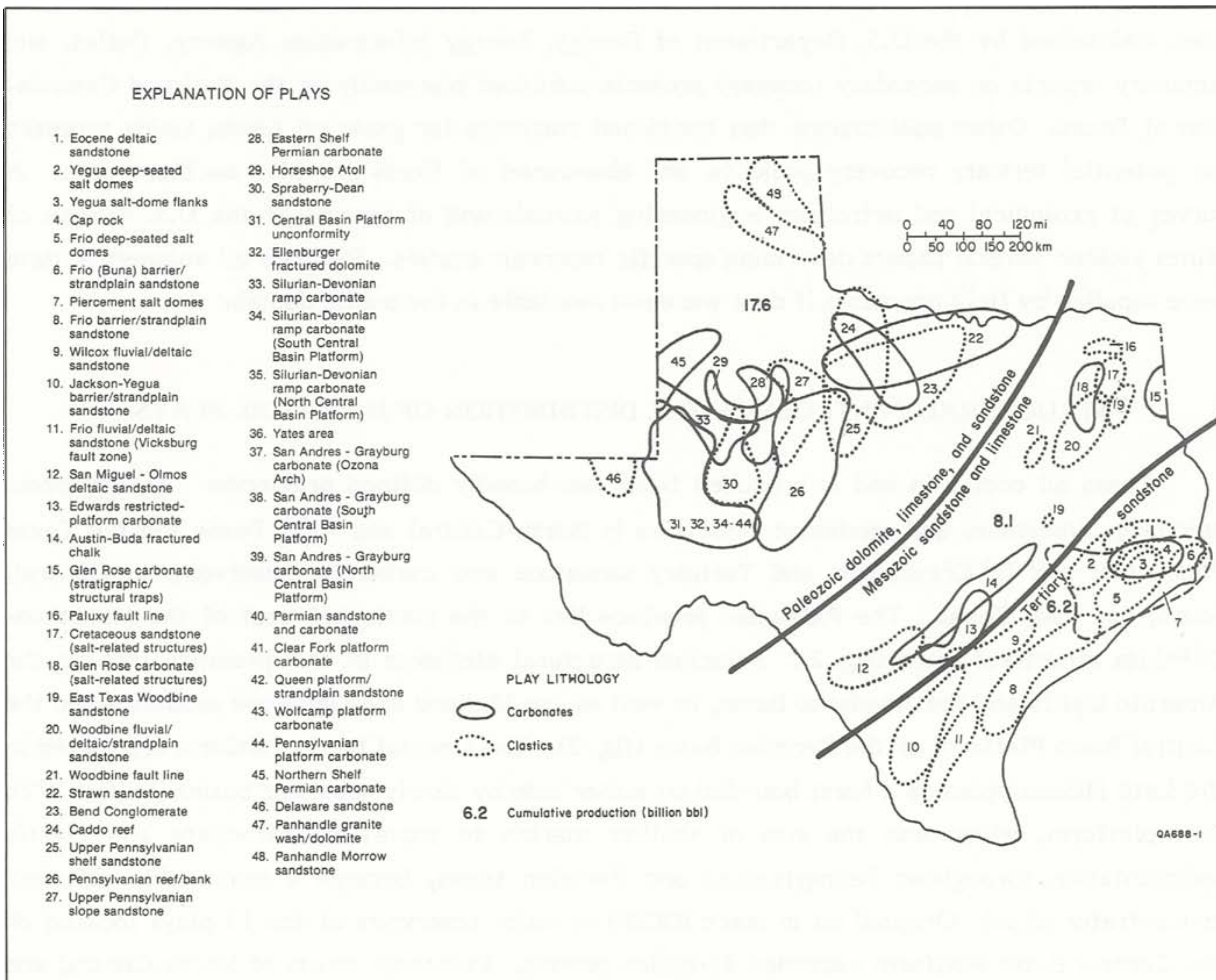


Figure 1. Geographic distribution of the 48 major oil plays in Texas, modified from Galloway and others (1983).

The principal objectives of the survey were (1) to characterize major oil reservoirs statewide and (2) to evaluate the potential for additional recovery from these reservoirs. Results of the first objective were published in the "Atlas of Major Texas Oil Reservoirs" by Galloway and others (1983). The target for additional recovery is described by Fisher and Galloway (1983) and in this paper, which also emphasizes the importance of reservoir genesis in defining oil accumulation and production patterns in Texas reservoirs.

SOURCES OF DATA

Hearing files maintained by the Railroad Commission of Texas, Central Records Section of the Oil and Gas Division, were the principal source of geological and engineering data for the selected reservoirs. Unitization, injection, maximum efficient recovery (MER), field rules, and discovery files proved particularly useful. Additional sources of data included oil and gas field files maintained by the U.S. Department of Energy, Energy Information Agency, Dallas, and summary reports on secondary recovery projects published biannually by the Railroad Commission of Texas. Other publications that contained statistics for giant oil fields, fields targeted for potential tertiary recovery projects, and abandoned oil fields provided ancillary data. A survey of geological and petroleum engineering journals and of reports of the U.S. Bureau of Mines yielded several papers describing specific reservoir studies. Reliable oil volumetric data were supplied by field operators if data were not available in the public domain.

STRUCTURAL CONTROLS ON THE DISTRIBUTION OF MAJOR OIL PLAYS

Texas oil occurs in and is produced from two broadly defined provinces: (1) Paleozoic dolomite, limestone, and sandstone reservoirs in North-Central and West Texas and the Texas Panhandle; and (2) Cretaceous and Tertiary sandstone and carbonate reservoirs in Central, South, and East Texas. The Paleozoic province lies to the north and west of the Marathon-Ouachita structural front (fig. 2). Principal structural elements in this province include the Amarillo Uplift and the Anadarko Basin, as well as the Midland and Delaware subbasins and the Central Basin Platform of the Permian Basin (fig. 2). The Central Basin Platform originated in the Late Mississippian as a horst bounded on either side by slowly subsiding basins (Mills, 1972). This platform, which was the site of shallow marine to supratidal carbonate and clastic sedimentation throughout Pennsylvanian and Permian times, became a remarkably efficient concentrator of oil. Original oil in place (OOIP) in major reservoirs of the 13 plays located on the Central Basin Platform exceeded 31 billion barrels. Paleozoic strata of North-Central and West Texas and the Texas Panhandle contained 73 percent of the OOIP of the 48 plays in the state (fig. 2, insert A).

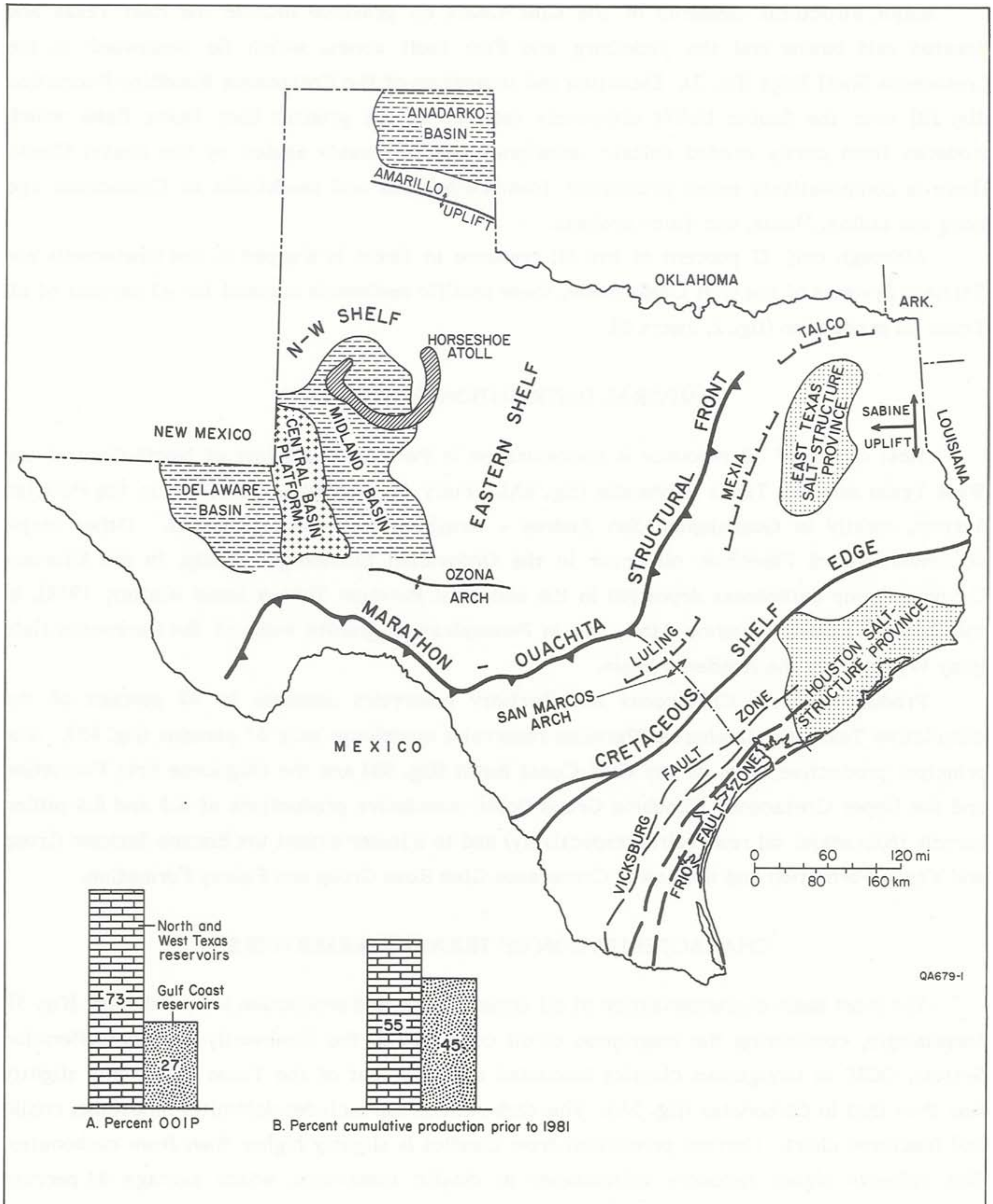


Figure 2. Major structural elements in Texas, modified from Galloway and others (1983). Original-oil-in-place and production statistics are given for the two principal hydrocarbon provinces of Texas.

Major structural elements of the Gulf Coast oil province include the East Texas and Houston salt basins and the Vicksburg and Frio fault zones, which lie basinward of the Cretaceous Shelf Edge (fig. 2). Elevation and truncation of the Cretaceous Woodbine Formation (fig. 3B) over the Sabine Uplift ultimately resulted in the prolific East Texas field, which produces from partly eroded deltaic sandstones unconformably sealed by the Austin Chalk. There is comparatively minor production from carbonates and sandstones of Cretaceous age along the Luling, Mexia, and Talco grabens.

Although only 27 percent of the oil resource in Texas is trapped in the Cretaceous and Tertiary Systems of the Gulf Coast Basin, these prolific sediments account for 45 percent of all Texas oil production (fig. 2, insert B).

TEMPORAL DISTRIBUTION OF TEXAS OIL

Most of Texas' oil resource is concentrated in Permian sediments of North-Central and West Texas and the Texas Panhandle (fig. 4A). Fully 58 percent is contained in the Permian System, mostly in Guadalupian San Andres - Grayburg carbonates (fig. 3A). Other major accumulations of Paleozoic oil occur in the Ordovician Ellenburger Group, in the Silurian-Devonian ramp carbonates deposited in the ancestral Permian Tobosa Basin (Galley, 1958), in the Pennsylvanian Horseshoe Atoll, and in Pennsylvanian granite wash of the Panhandle field (play 47, fig. 1) in the Anadarko Basin.

Production from Cretaceous and Tertiary reservoirs amounts to 45 percent of the cumulative Texas total, whereas Permian reservoirs contribute only 37 percent (fig. 4B). The principal productive units of the Gulf Coast Basin (fig. 3B) are the Oligocene Frio Formation and the Upper Cretaceous Woodbine Group (joint cumulative productions of 4.5 and 6.4 billion barrels from major oil reservoirs, respectively) and to a lesser extent the Eocene Jackson Group and Yegua Formation and the Lower Cretaceous Glen Rose Group and Paluxy Formation.

CHARACTERIZATION OF TEXAS OIL RESERVOIRS

The most basic characterization of oil accumulation and production is by lithology (fig. 5). Surprisingly, considering the magnitude of oil contained in the dominantly carbonate Permian System, OOIP in terrigenous clastics amounted to 47 percent of the Texas total, only slightly less than that in carbonates (fig. 5A). The carbonate group includes dolomite, limestone, chalk, and fractured chert. Current production from clastics is slightly higher than from carbonates. This reflects higher recovery efficiencies in clastic reservoirs, which average 41 percent statewide, as compared with 35 percent for carbonate reservoirs (fig. 5B).

Reservoirs are further characterized according to depositional origin. The 48 major oil plays of Texas are grouped into 5 clastic and 6 carbonate depositional systems (figs. 6 and 10).

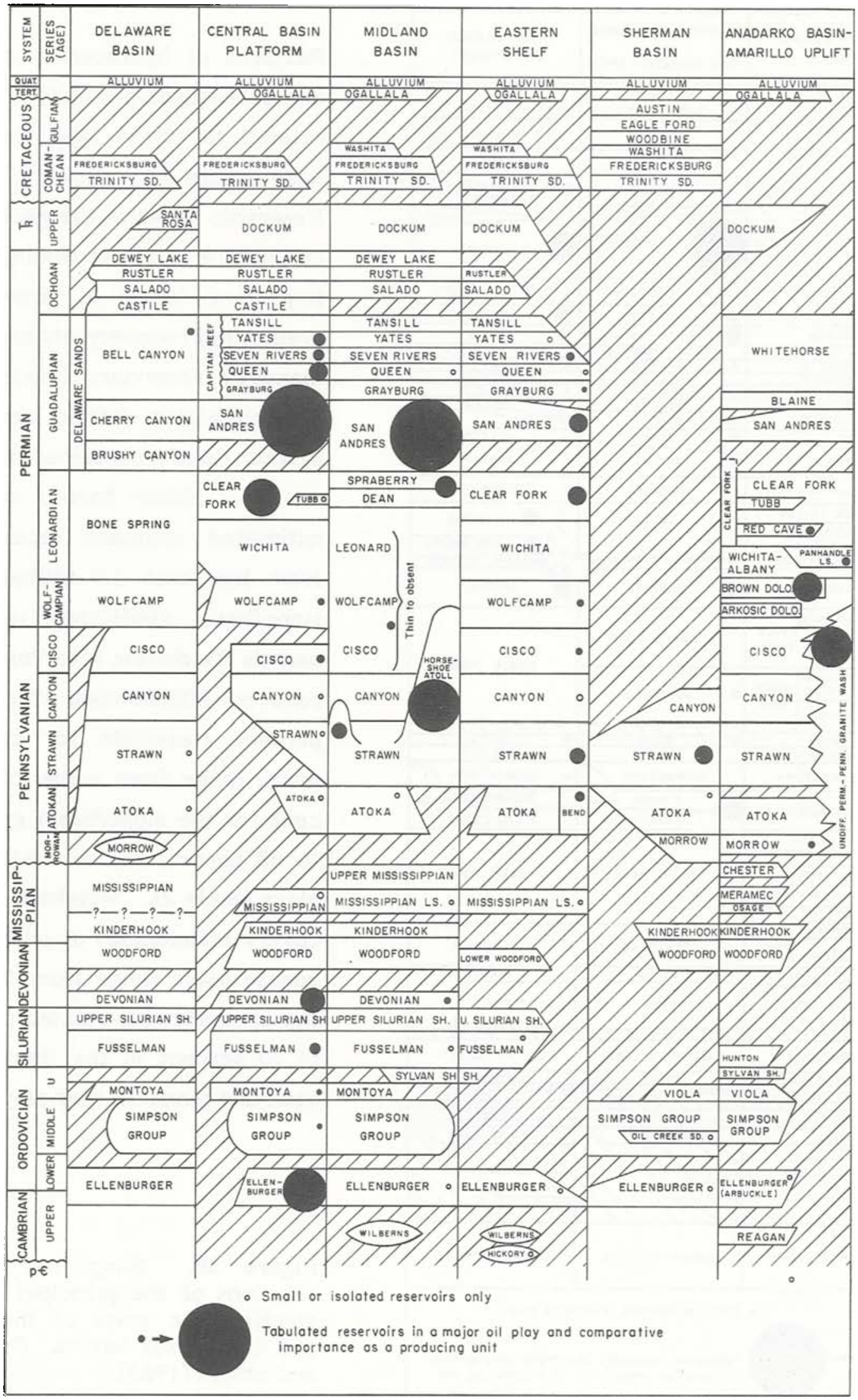
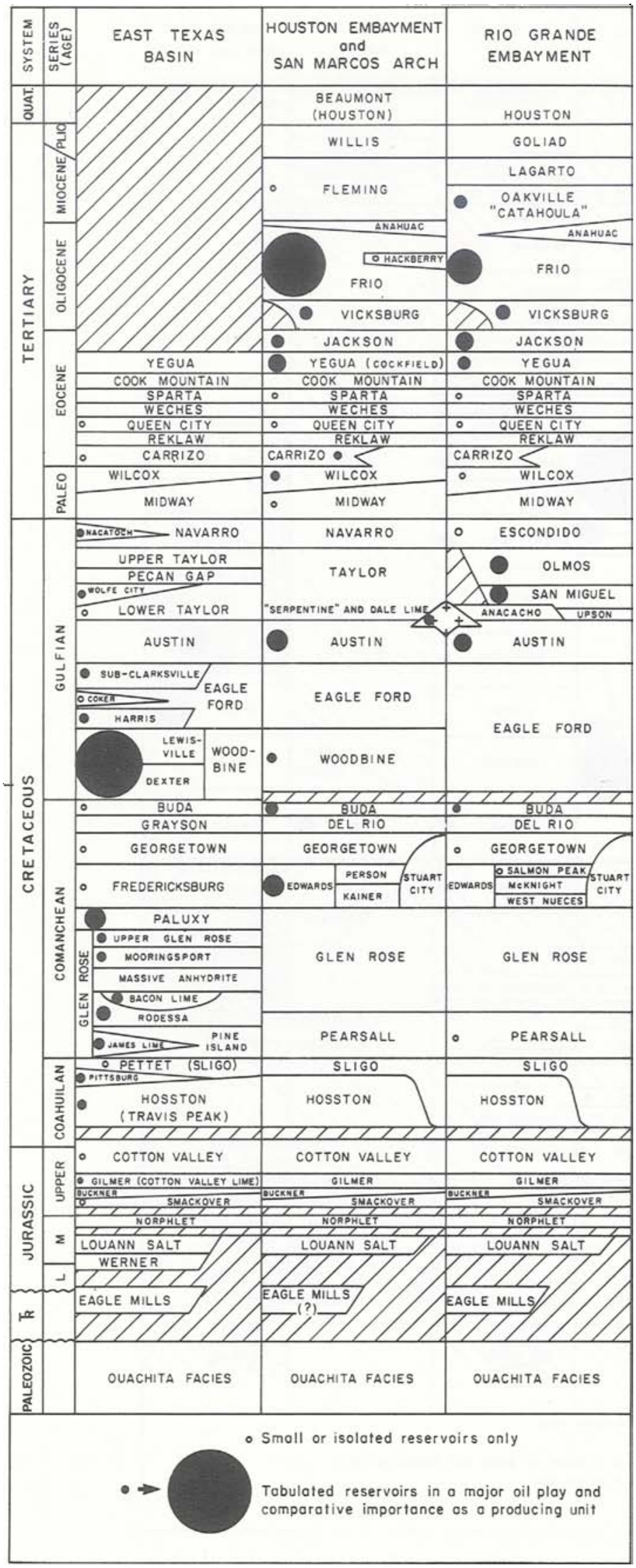


Figure 3A. Simplified geologic age relations of the principal oil-producing stratigraphic units of the North-Central, Panhandle, and West Texas basins. From Galloway and others (1983).



Patterns of hydrocarbon accumulation and subsequent production are strongly related to facies type, resulting in a wide range of recovery efficiencies. Reservoir genesis--the geological origin and nature of the producing zone--is an important factor in determining (and predicting) recovery efficiency in well-managed reservoirs (tables 2 and 3). Fluvial/deltaic, deltaic, and slope/basin systems each contained between 11.6 and 13.2 billion barrels of OOIP, yet estimated ultimate recoveries range from less than 1.0 billion barrels for slope/basin sandstones to 8.5 billion barrels for deltaic reservoirs. Weighted recovery efficiencies, which average 41 percent statewide for clastic reservoirs, range from a low of only 8 percent for the slope/basin group of plays to 68 percent for the deltaic group of plays (table 2). Weighted ultimate recovery efficiencies of oil from the carbonate plays range from 26 percent in the unconformity-related play to a high of 50 percent in the three deep-water atoll and pinnacle-reef plays (table 3).

Figure 3B. Simplified geologic age relations of the principal oil-producing stratigraphic units of the Gulf Coast and East Texas Basins. From Galloway and others (1983).

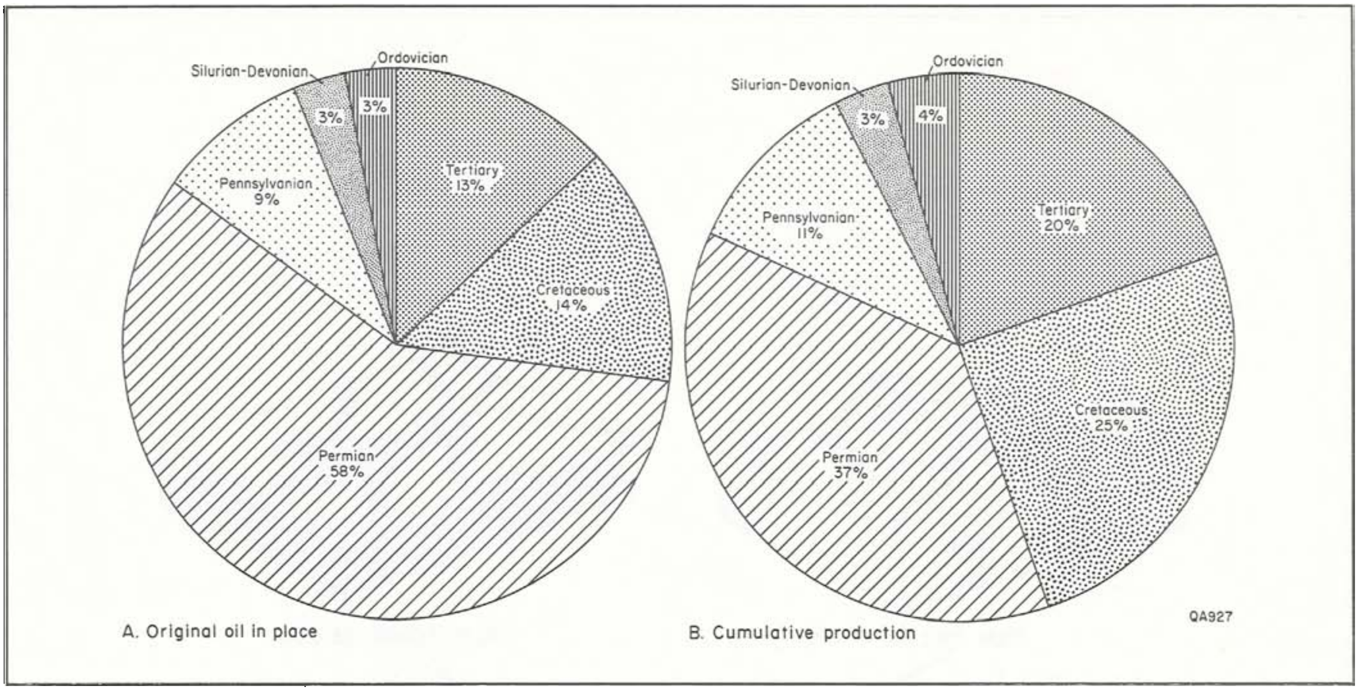


Figure 4. A. Temporal distribution of OOIP in Texas. B. Cumulative oil production by reservoir age (data from the Railroad Commission of Texas, 1982).

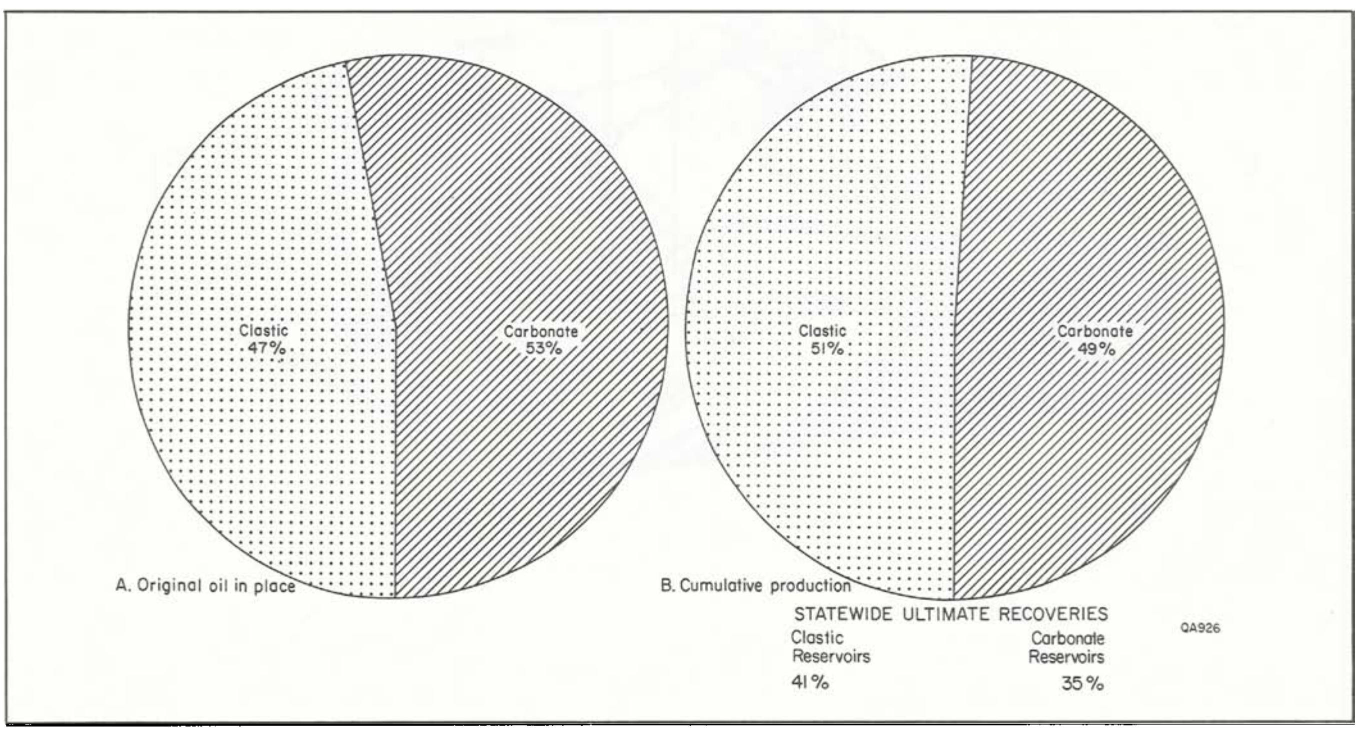


Figure 5. Distribution of major oil occurrences in terrigenous clastic reservoirs and in carbonate reservoirs including limestones, dolomites, chalk, and fractured chert. A. Clastic reservoirs contained a lower OOIP resource. B. However, as a result of better reservoir performance, recovery is slightly higher than from carbonate reservoirs.

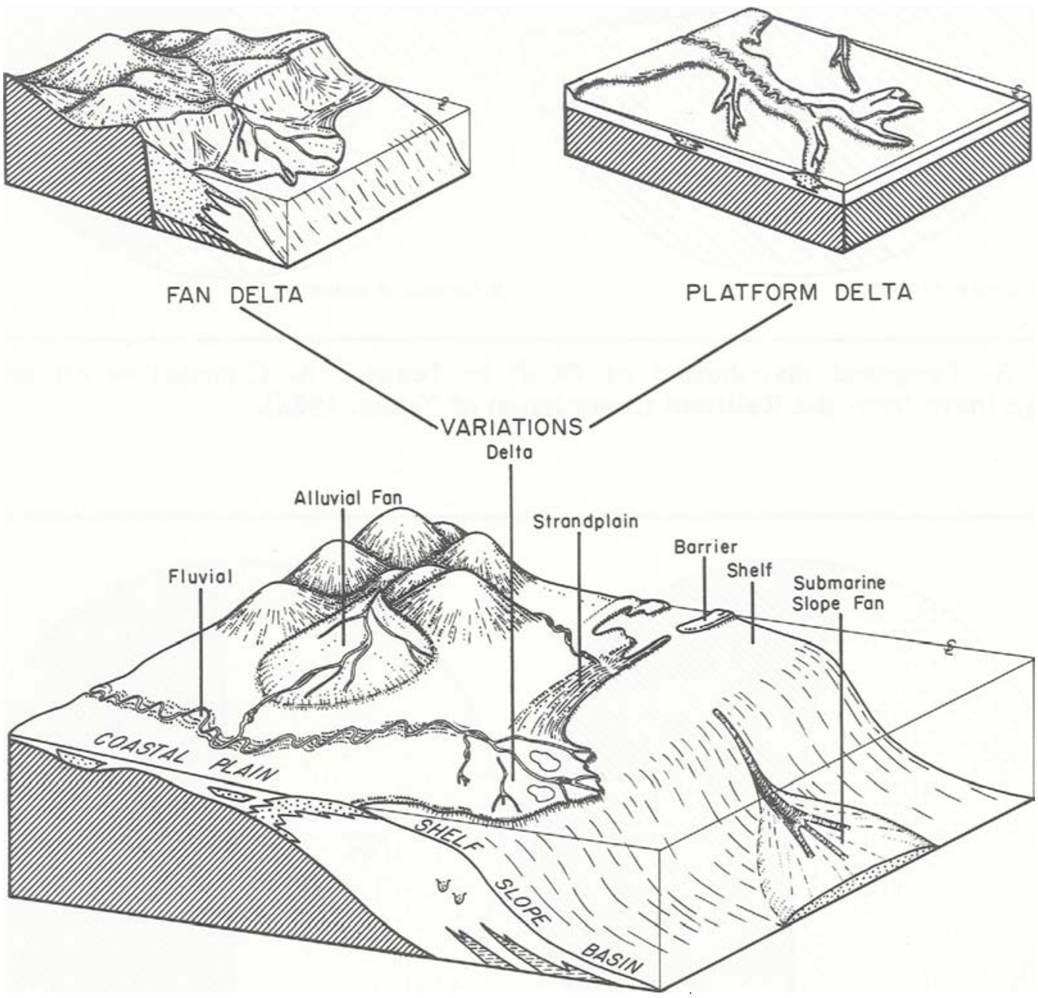


Figure 6. Clastic depositional systems that typically host oil resources in Texas, from Galloway and others (1983). Fluvial/deltaic (for example, fan-delta and interstratified fluvial and deltaic facies tracts), deltaic, and slope and basinal sandstones contain 84 percent of the oil resource in clastic rocks in Texas.

Clastic Depositional Systems

Fluvial Systems

The three plays of fluvial origin contained 1.5 billion barrels of oil, the least of all the clastic systems. This amounts to 3 percent of the OOIP in clastic reservoirs in Texas (fig. 7A). However, this percentage is low because much of the oil in fluvial systems occurs at or near the transition with deltaic units and thus is included in fluvial/deltaic plays.

Conventional oil recoveries from complex fluvial channel systems are typically low to moderate, displaying a weighted average of 36 percent (table 2). Coarse-grained, sand-rich, braided-stream deposits such as some of the Bend Conglomerate reservoirs (play 23, fig. 1) are exceptions, having recoveries exceeding 40 percent. Well-engineered reservoir development and the application of genetic stratigraphy in positioning infill development wells also have resulted in high recovery efficiencies, such as in the Neches (Woodbine) field (play 20). On the basis of current production trends, fluvial deposits are estimated to have an ultimate production of only 3 percent of the total yield from clastic reservoirs in Texas (fig. 7B).

Fluvial/Deltaic Systems

Fluvial/deltaic plays include fan-delta deposits, such as those of the Panhandle granite-wash/dolomite play, and superposed sandstone sequences where oil is produced from interbedded

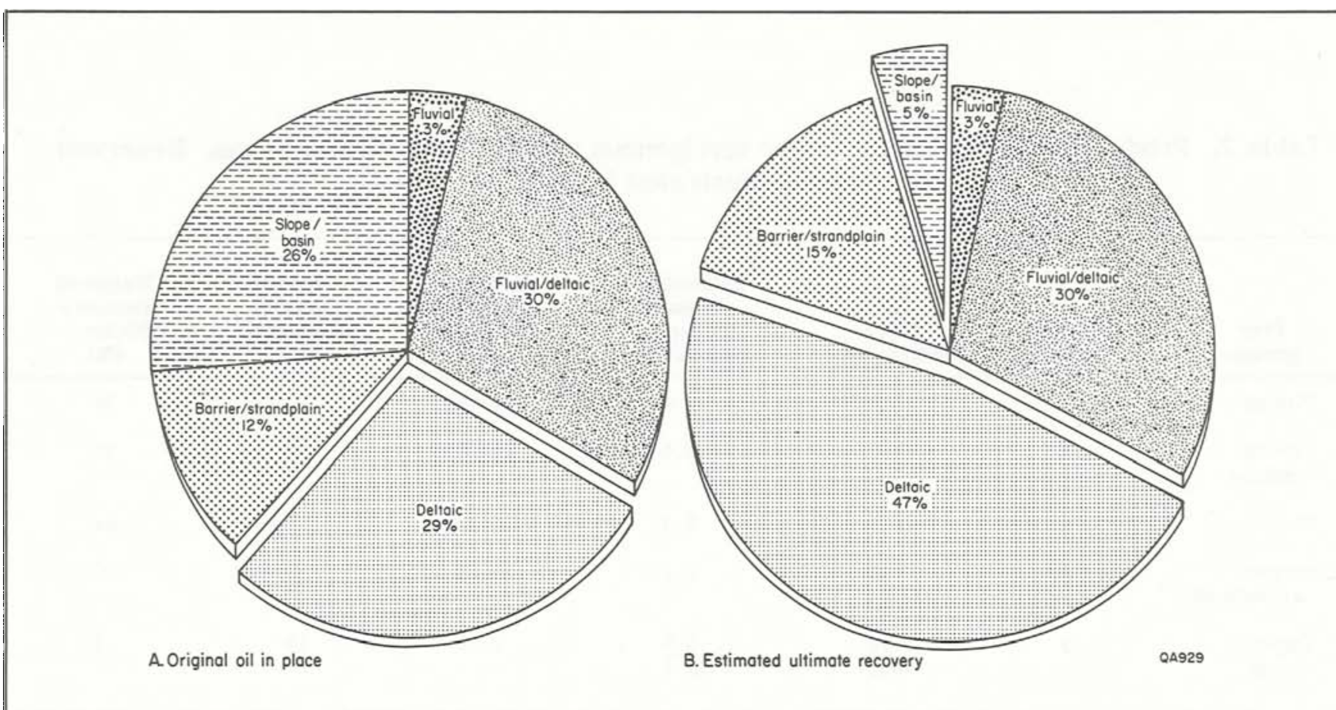


Figure 7. Exploded pie diagrams illustrating the relation between reservoir genesis and the patterns of (A) oil accumulation in and (B) subsequent production from clastic reservoirs. Production from deltaic reservoirs accounts for almost half of all production from clastic deposits.

deltaic and fluvial facies tracts, such as in the Woodbine fluvial/deltaic/strandplain sandstone play of the East Texas salt basin (fig. 8). Fluvial/deltaic deposits account for 30 percent of the OOIP in clastic reservoirs in Texas (fig. 7A).

Fluvial/deltaic deposits contain many facies variations, which exhibit great textural and compositional heterogeneity. Average reservoir yields, which range from 24 to 69 percent, reflect the complexity of this class of reservoirs (table 2). Barring extensive diagenetic modification, the coarse grain size and consequent high initial permeability of the reservoir sandstones and conglomerates compensate somewhat for extensive compartmentalization in the fluvial/deltaic plays. Fluvial/deltaic reservoirs are projected to yield 30 percent of the ultimate production from clastic reservoirs in Texas (fig. 7B).

Deltaic Systems

Deltaic deposits contained 29 percent of the OOIP in clastic reservoirs (fig. 7A). The most prolific producer from these reservoirs is the famous East Texas (Woodbine) field, which has the highest current cumulative production of any reservoir in the United States (more than 4.7 billion barrels). Other large deltaic plays are the Yegua and Frio sequences that are warped over deep-seated salt domes in the Houston salt basin (fig. 8).

Production from deltaic systems overshadows reservoir yields from all other depositional systems (fig. 7B). Deltaic sands are expected to produce almost half of all the oil obtained from clastic reservoirs in Texas. The great volume of oil recovered from the deltaic deposits of

Table 2. Production statistics for major terrigenous clastic reservoirs in Texas. Reservoir genesis is illustrated in figure 6.

Play genesis	Number of plays	OOIP (billion bbl)	Estimated ultimate recovery (billion bbl)	Range of recovery efficiency (%)	Average recovery efficiency* (%)	Weighted recovery efficiency† (%)
Fluvial	3	1.5	0.6	24-49	42	36
Fluvial/ deltaic	8	13.2	5.4	24-69	45	40
Deltaic	6	12.6	8.5	21-80	46	68
Barrier/ strandplain	3	5.5	2.7	38-69	53	50
Slope/ basin	3	11.6	0.9	6-21	15	8
		44.5	18.1			41

*Average recovery efficiency is the average of the recovery efficiencies of each play in the system.

†Weighted recovery efficiency for each system is determined by dividing the estimated total ultimate recovery for all the plays in the system by the total OOIP in the system.

the East Texas field biases the estimated ultimate recovery (fig. 7B); however, most of the deltaic plays have recovery efficiencies greater than the average for clastic reservoirs (table 2).

Individual plays of deltaic origin exhibit wide ranges of recovery efficiencies (table 2). However, close examination shows a predictable correlation between reservoir productivity and type of deltaic system (Galloway and others, 1982). Fluvial-dominated deltas, which occur in

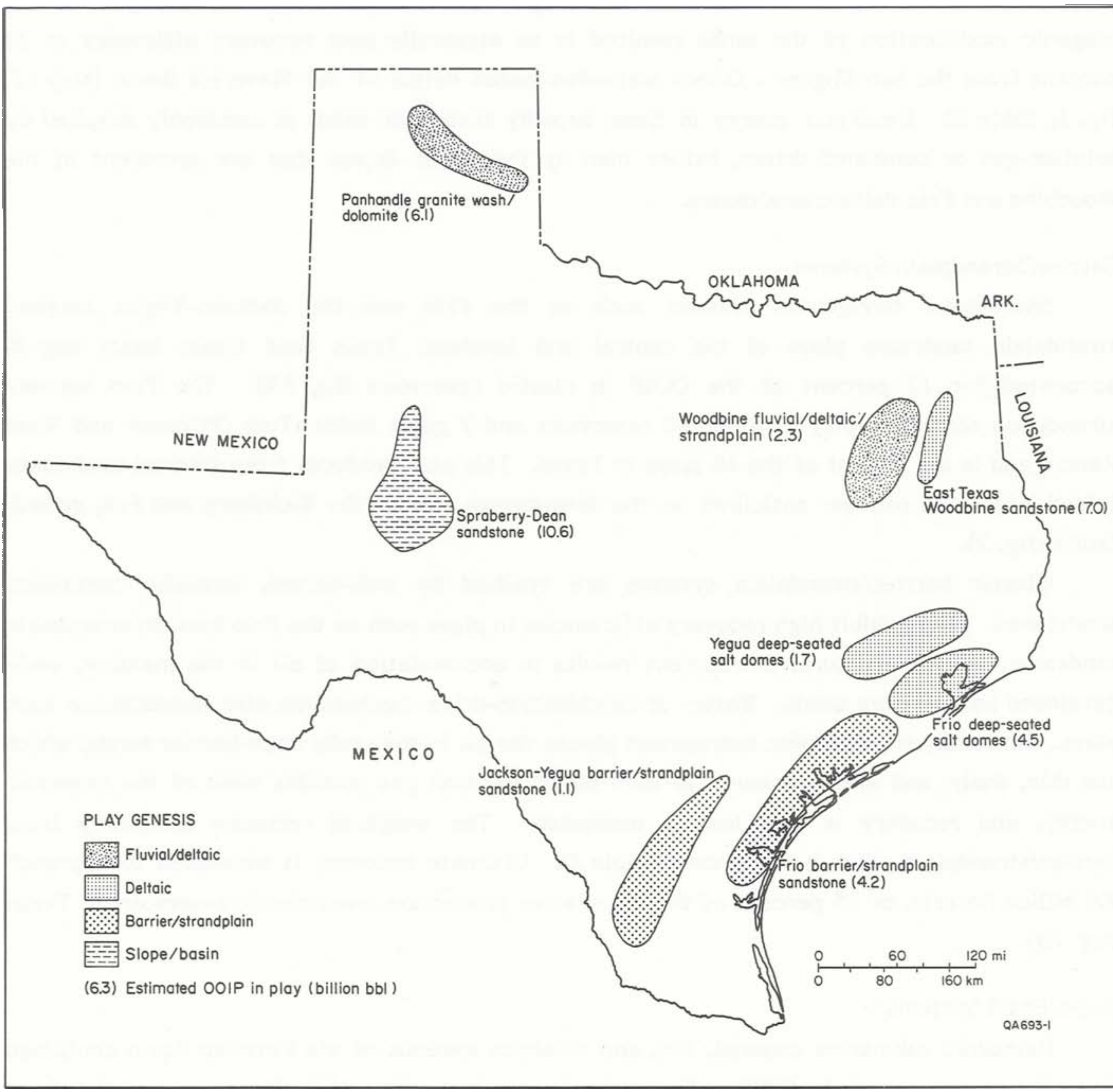


Figure 8. Principal clastic plays of Texas that contained more than 1 billion barrels of OOIP. The eight plays account for 81 percent of the oil in major clastic reservoirs in Texas. None of the fluvial plays held a billion barrels of OOIP.

such plays as the Strawn sandstone (play 22, fig. 1), the Upper Pennsylvanian shelf sandstone (play 25), and the Frio fluvial/deltaic sandstone (play 11), historically have low to average recovery efficiencies. In contrast, wave-dominated deltas such as much of the Woodbine (plays 19 and 20, fig. 1), which includes the East Texas field, exhibit recovery efficiencies that are well above average. Large deltas such as those of the Frio deep-seated salt-domes play of the upper Gulf Coast Basin (play 5, fig. 1), which underwent considerable wave modification and produce by water drives with the aid of gas-cap expansion and gravity drainage, are also highly productive. Reworking of foundered deltas during coastal onlap combined with diagenetic and biogenic modification of the sands resulted in an atypically poor recovery efficiency of 21 percent from the San Miguel - Olmos wave-dominated deltas of the Maverick Basin (play 12, fig. 1; table 2). Reservoir energy in these broadly lenticular sands is commonly supplied by solution-gas or combined drives, rather than by the water drives that are prevalent in the Woodbine and Frio deltaic sandstones.

Barrier/Strandplain Systems

Shore-zone terrigenous clastics such as the Frio and the Jackson-Yegua barrier/strandplain sandstone plays of the central and southern Texas Gulf Coast Basin (fig. 8) accounted for 12 percent of the OOIP in clastic reservoirs (fig. 7A). The Frio barrier/strandplain sandstone play contains 46 reservoirs and 2 giant fields (Tom O'Connor and West Ranch) and is the largest of the 48 plays in Texas. This play produces from stacked sandstones folded into broad rollover anticlines on the downthrown side of the Vicksburg and Frio growth faults (fig. 2).

Clastic barrier/strandplain systems are typified by well-sorted, laterally continuous sandstones. They exhibit high recovery efficiencies in plays such as the Frio barrier/strandplain sandstone, where structural entrapment results in accumulation of oil in the massive, well-developed barrier-core sands. Water- or combination-drive mechanisms also characterize such plays. However, stratigraphic entrapment places the oil in the updip back-barrier sands, which are thin, shaly, and discontinuous. In such plays, solution gas provides most of the reservoir energy, and recovery is only low to moderate. The weighted recovery efficiency from barrier/strandplain plays is 50 percent (table 2). Ultimate recovery is estimated to approach 2.4 billion barrels, or 15 percent of the cumulative production from clastic reservoirs in Texas (fig. 7B).

Slope/Basin Systems

Paleozoic submarine channel, fan, and turbidite systems of the Permian Basin contained more than a quarter of the OOIP in Texas clastic reservoirs (fig. 7A). The largest of the three deep-water basinal sandstone plays is the Permian Spraberry-Dean trend of the Midland Basin, which held approximately 10.6 billion barrels of in-place oil (fig. 8). Total OOIP in the three deep-water plays was 11.6 billion barrels. The reservoirs are commonly fine-grained siltstones and sandstones that display low permeabilities and high residual oil saturations. Internal compartmentalization and heterogeneity are inherent because of the depositional origin of the reservoirs. Reservoir energy is commonly supplied by solution gas. Because of poor reservoir quality and inefficient reservoir drive mechanisms, recovery efficiencies are consistently low; only 8 percent of the OOIP has been recovered from this class of reservoirs (table 2). Slope/basin systems are anticipated to yield only 5 percent of the total production from clastic reservoirs of Texas (fig. 7B). Considering that these deep-water clastics once held more than a quarter of the oil resource in all clastic reservoirs (fig. 7A), it is obvious that these submarine fan/turbidite systems contain substantial targets for additional recovery.

Carbonate Depositional Systems

Restricted-Platform Systems

In contrast to the distribution of OOIP in clastic reservoirs, where the bulk of the resource is fairly evenly distributed among fluvial/deltaic, deltaic, barrier/strandplain, and slope/basin systems, the distribution of OOIP in carbonate sequences is overwhelmingly concentrated in dolomitized restricted-platform deposits (figs. 9A and 10). Fully 61 percent of

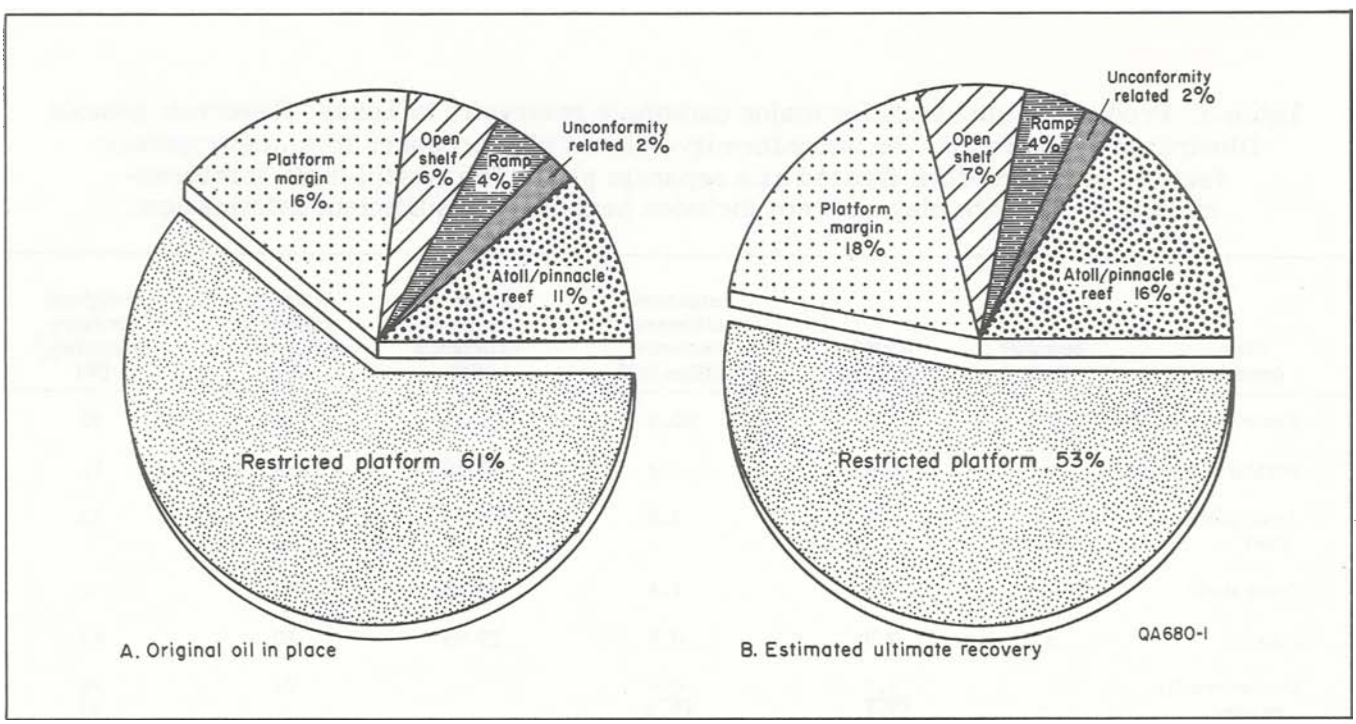


Figure 9. Exploded pie diagrams illustrating the relation between reservoir genesis and the patterns of (A) oil accumulation in and (B) subsequent production from carbonate reservoirs. Restricted-platform deposits account for more than half of the OOIP in carbonate sequences and will produce more oil than all the other carbonate systems combined if current production trends persist.

the OOIP in carbonates is contained in these reservoirs, which are composed of a spectrum of interrelated back-reef facies, including restricted-shelf, lagoonal, and tidal-flat deposits. The nine plays of restricted-platform origin accounted for almost 34 billion barrels of OOIP (table 3).

With the exception of the small cluster of pools in the Edwards Group on the San Marcos Arch, most of the major restricted-platform plays are on the Central Basin Platform and the northern and eastern shelves of the Permian Basin. The 12 plays illustrated in figure 11 originally contained more than 52 billion barrels of oil, or 86 percent of the OOIP in carbonates. The productive core of the Permian Basin is illustrated in greater detail in figure 12, which further emphasizes the enormous volumes of oil that are contained in restricted-platform deposits. These Permian reservoirs are principally of Guadalupian (San Andres - Grayburg) and Leonardian (Clear Fork) age.

Restricted-platform deposits do not readily release entrapped oil. Ultimate recovery by primary and secondary methods is estimated to be 10.3 billion barrels, or just 30 percent of the original resource (table 3). These reservoir deposits originated on shallow-water platforms under arid and evaporitic climatic conditions. Diagenesis of original sediments produced extensive beds of dolomite that typically exhibit low porosity and permeability values. The resulting reservoirs are highly stratified and display moderate to high residual oil saturations following primary and secondary production. Isolation of permeable zones within lithologically

Table 3. Production statistics for major carbonate reservoirs in Texas. Reservoir genesis illustrated in figure 10. The unconformity-related play produces from many genetic facies and is therefore treated as a separate play. The Austin-Buda fractured-chalk and cap-rock plays are not included because of insufficient information.

Play genesis	Number of plays	OOIP (billion bbl)	Estimated ultimate recovery (billion bbl)	Range of recovery efficiency (%)	Average recovery efficiency* (%)	Weighted recovery efficiency† (%)
Restricted platform	9	33.6	10.3	21-48	32	30
Platform margin	5	8.6	3.5	23-50	34	41
Atoll/pinnacle reef	3	6.0	3.0	44-51	48	50
Open shelf	2	3.5	1.4	38-40	39	40
Ramp	3	2.0	0.8	29-49	40	40
Unconformity-related	1	1.3	0.4	-	26	26
		55.1	19.3			35

*Average recovery efficiency is the average of the recovery efficiencies of each play in the system.

†Weighted recovery efficiency for each system is determined by dividing the estimated total ultimate recovery for all the plays in the system by the total OOIP in the system.

heterogeneous sequences results in dominance of solution-gas drives. Together, the comparatively inefficient drive mechanism, stratification, and combined depositional and diagenetic heterogeneity result in low to moderate recovery efficiencies. However, because of the enormous reserves of oil that these reservoirs contain, they will still account for 53 percent of all production from carbonates (fig. 9B).

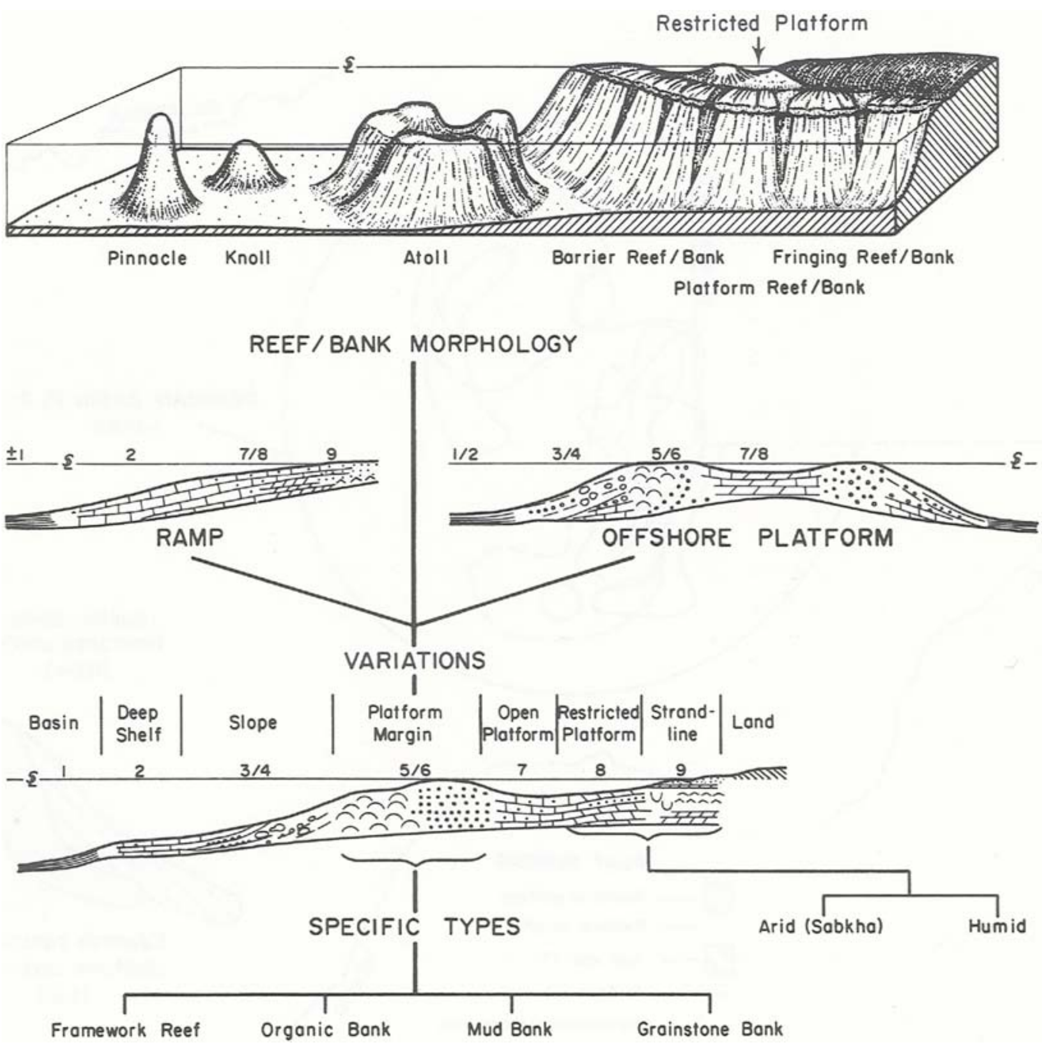


Figure 10. Carbonate depositional systems that typically host oil resources in Texas, from Galloway and others (1983); modified from Wilson (1975). Restricted-platform deposits, which lie on the landward side of fringing or barrier reefs and banks, contain the largest resources of oil in carbonate rocks in Texas. Platform-margin and atoll/pinnacle-reef systems also contain large volumes of oil.

Platform-Margin Systems

Platform-margin deposits, which include both reefal limestones and nonreefal limestones and sandstones draped over the shelf margin, account for 16 percent of the OOIP in carbonates (fig. 9A). An example is the Permian sandstone and carbonate play on the west flank of the Central Basin Platform (fig. 12), where reservoir facies are porous Permian carbonates and Guadalupian sandstones (San Andres through Yates, fig. 3A). Platform-margin deposits contained more than 8.6 billion barrels of OOIP (table 3).

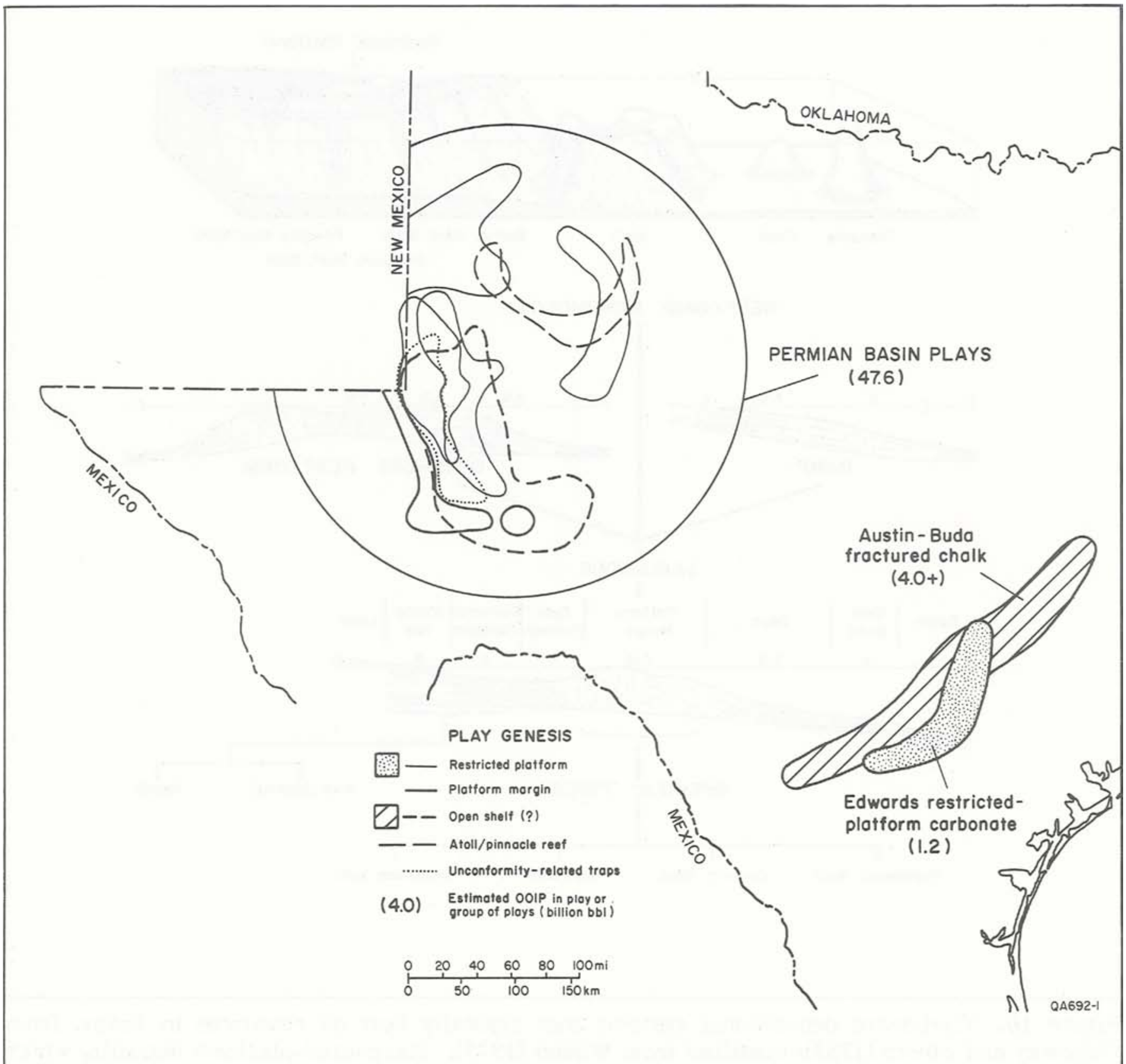


Figure 11. Principal carbonate plays of Texas that contained more than 1 billion barrels of OOIP. For more detailed illustration of the Permian Basin plays, see figure 12.

Organic reefs and banks along shallow-water, submerged platform edges display diverse lithologies and diagenetic histories. Unlike the reefs that grew upward from deep-water open shelves and were encased in shale, the platform-margin reefs and banks commonly grade laterally and vertically into a variety of sealing or less permeable strata. Further, facies belts tend to be thin, narrow, highly elongate, and internally complex. Reservoir quality commonly reflects great modification of original sediment texture. At one extreme, leaching by fresh water has produced vuggy, cavernous porosity (and an excellent reservoir) at Yates field

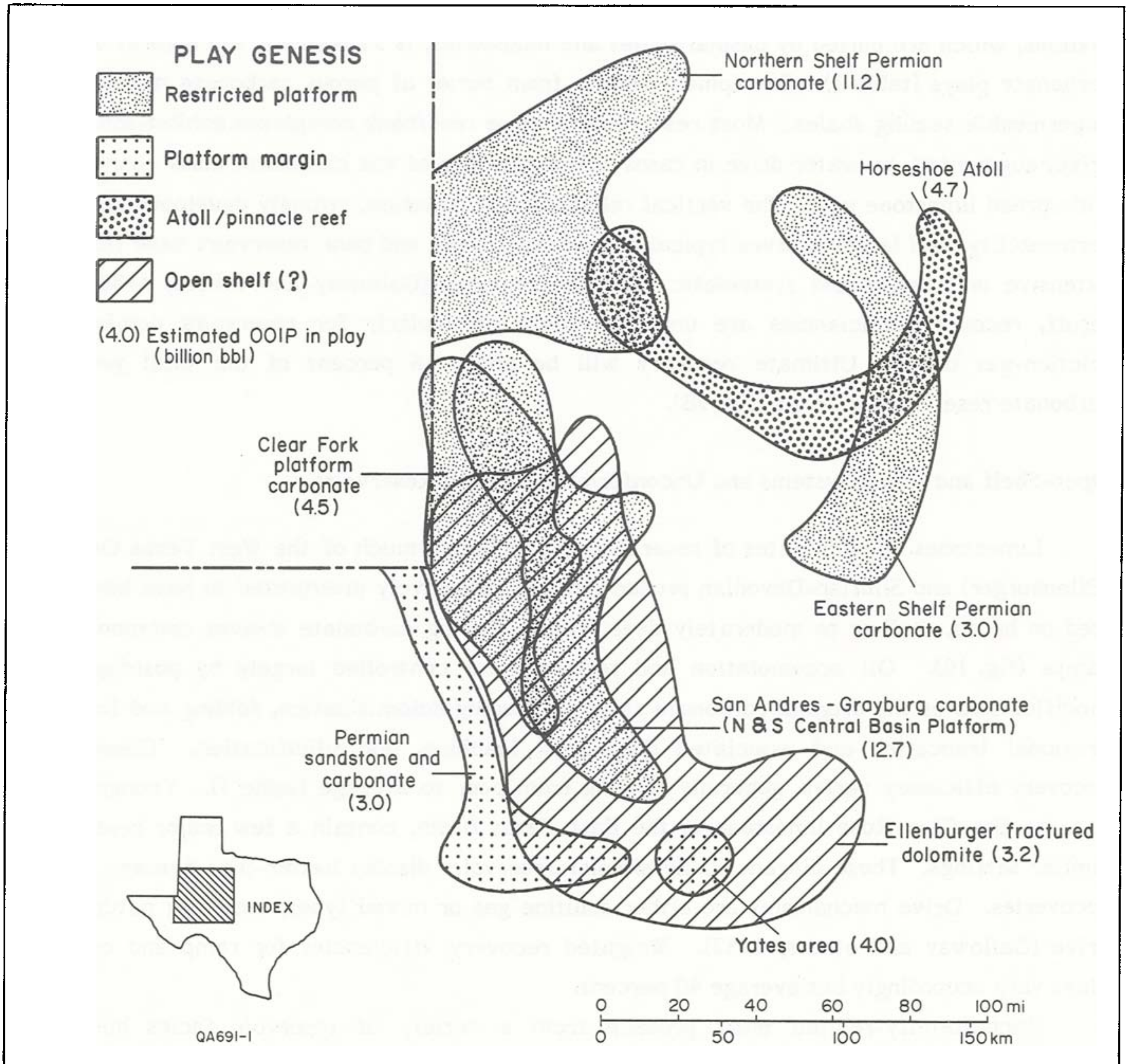


Figure 12. Major carbonate plays of the Permian Basin. The Central Basin Platform was the site of the concentration of enormous volumes of oil, principally in restricted-platform carbonates.

(fig. 12), where ultimate recovery will be 50 percent of the OOIP on the basis of current production trends (table 3). More commonly, permeability is highly stratified and lenticular, and recovery efficiencies are low, averaging 34 percent (table 3). The weighted recovery from platform-margin systems is 41 percent (table 3) because of high yield from the Yates field.

Atoll/Pinnacle-Reef Systems

Open-shelf atoll, pinnacle-reef, and patch-reef plays such as the Horseshoe Atoll (fig. 12) account for 11 percent of the OOIP in carbonates. The weighted recovery of oil from these systems, which are buried by basinal shales and mudstones, is 50 percent, the highest of all the carbonate plays (table 3). Entrapment results from burial of porous carbonate mounds within impermeable sealing shales. Most reservoirs in these reef/bank complexes exhibit solution-gas drive, augmented by water drive in cases where the base of the carbonate mass connects to a widespread limestone unit. The vertical relief, lateral isolation, strongly developed layering of permeability, and large reserves typical of open-shelf reef and bank reservoirs have resulted in extensive unitization and systematic field development (Galloway and others, 1982). As a result, recovery efficiencies are unusually high, particularly for reservoirs dominated by solution-gas drive. Ultimate recovery will be about 16 percent of the total yield from carbonate reservoirs in Texas (fig. 9B).

Open-Shelf and Ramp Systems and Unconformity-Related Reservoirs

Limestones and dolomites of several plays, including much of the West Texas Ordovician (Ellenburger) and Silurian-Devonian production, are tentatively interpreted to have been deposited on broad, shallow to moderately deep, gently sloping carbonate shelves commonly called ramps (fig. 10). Oil accumulation and recovery are controlled largely by postdepositional modifications of the original carbonate strata, including dolomitization, folding and fracturing, erosional truncation and associated diagenesis, leaching, and silicification. Consequently, recovery efficiency varies, generally ranging from poor to average (table 3). Younger strata, such as the Glen Rose limestone in the East Texas Basin, contain a few major reservoirs in similar settings. These diagenetically simpler reservoirs display better-than-average ultimate recoveries. Drive mechanisms are either solution gas or mixed types, including natural water drive (Galloway and others, 1982). Weighted recovery efficiencies for ramp and open-shelf plays vary accordingly but average 40 percent.

Unconformity-related traps produce from a variety of reservoir facies but exhibit consistently low recoveries, averaging only 26 percent. In shelf, ramp, and unconformity-related reservoirs, OOIP amounts to 12 percent and ultimate recovery 13 percent of the total for Texas carbonates (fig. 9).

Prediction of Reservoir Recovery Efficiency

The efficiency of primary oil recovery is largely determined by three groups of variables: (1) basic rock properties, including lithology, permeability, and continuity, which are in turn determined by reservoir genesis, (2) drive mechanism (reservoir energy), and (3) fluid properties. A cross plot of reservoir genesis and drive mechanism versus recovery efficiency shows well-defined trends of decreasing oil recovery in both clastic and carbonate systems (fig. 13). In clastic reservoirs, the highest recoveries occur from water-driven deltaic sandstones and the lowest from slope/basin sandstones, where energy is supplied by solution gas. Recovery efficiencies of the plays vary from 8 to 80 percent. The carbonate plays do not exhibit as broad

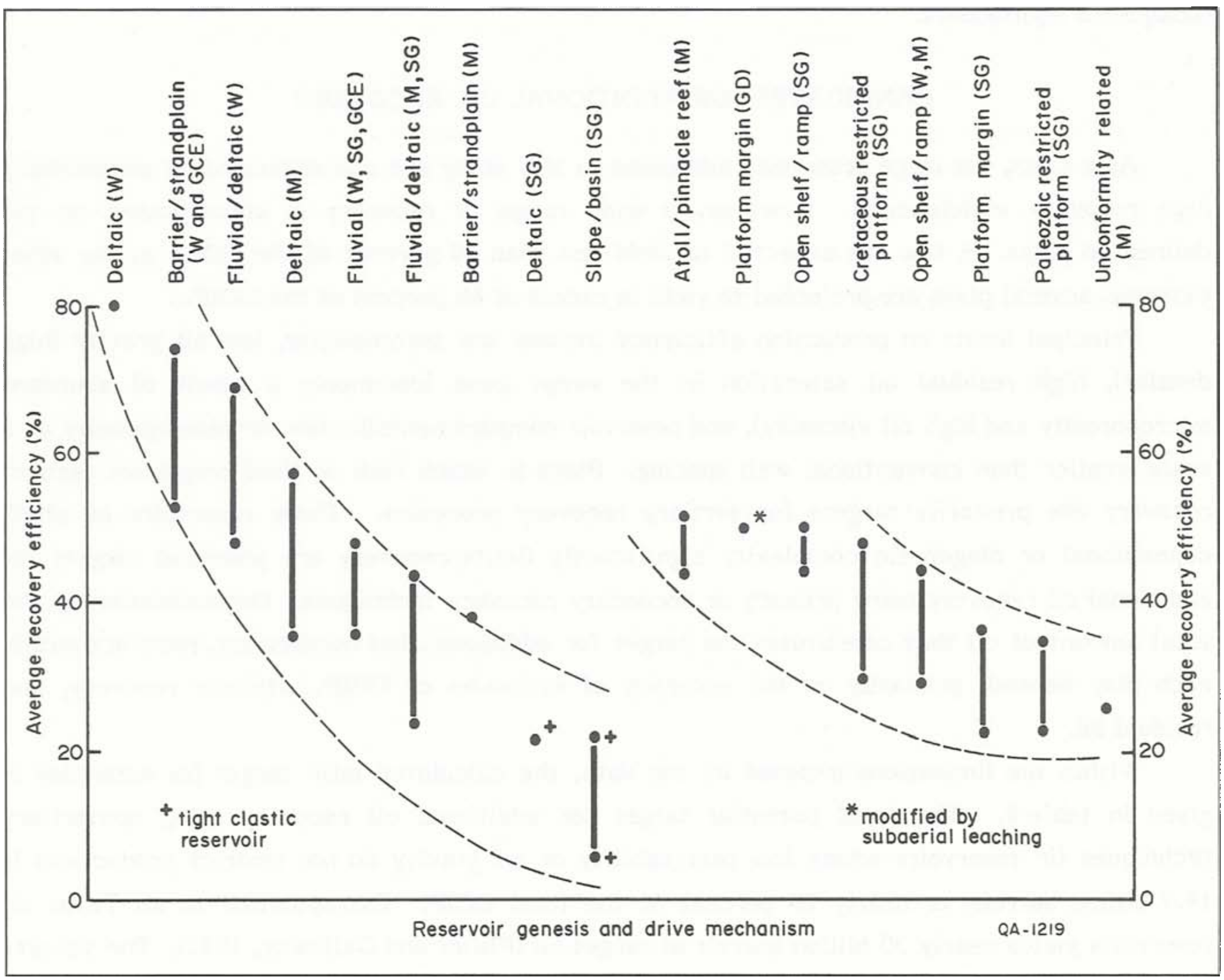


Figure 13. Cross plot of recovery efficiency range versus reservoir genesis and drive mechanism for major clastic and carbonate oil reservoirs in Texas. Reservoir genesis and drive mechanism define predictable trends in recovery efficiency. Drive mechanisms: W - water; GCE - gas-cap expansion; GD - gravity drainage; SG - solution gas; M - mixed (some combination of W, GCE, and SG).

a range of recovery efficiencies; however, a similar trend of decreasing recovery corresponds to increasing depositional and diagenetic complexity (fig. 13).

The average recovery from a reservoir or group of reservoirs may be reasonably predicted by cross plotting the genetic history of the reservoir, the drive mechanism, and the oil gravity. With the exception of tight sandstones (slope/basin plays and the San Miguel - Olmos deltaic sandstone play), which have lower recoveries, the recoveries from clastic reservoirs will equal or exceed those from carbonate reservoirs. In general, water-driven shore-zone reservoirs, such as deltaic and barrier/strandplain deposits, will produce more in-place oil than will their updip fluvial or downdip deep-water counterparts. In contrast, carbonate reservoirs of deep-water origin, such as atoll/pinnacle-reef and open-shelf/ramp systems, are more likely to exhibit high recovery efficiencies than are their depositionally and diagenetically complex, shallow subaqueous equivalents.

CANDIDATES FOR ADDITIONAL OIL RECOVERY

As a class, the large reservoirs addressed in this study are characterized by anomalously high recovery efficiencies. However, a wide range of recovery is encompassed by the delineated plays. A few are expected to yield less than 10 percent of the OOIP; at the other extreme, several plays are projected to yield in excess of 60 percent of the OOIP.

Principal limits on production efficiency include low permeability, low oil gravity (high density), high residual oil saturation in the swept zone (commonly a result of abundant microporosity and high oil viscosity), and reservoir compartmentalization or heterogeneity at a scale smaller than conventional well spacing. Plays in which rock or fluid properties restrict recovery are primarily targets for tertiary recovery processes. Those reservoirs in which depositional or diagenetic complexity significantly limits recovery are potential targets for additional oil recovery using primary or secondary recovery techniques. Determination of the total amount of oil that constitutes the target for additional, but nontertiary, recovery within each play depends primarily on the accuracy of estimates of OOIP, ultimate recovery, and residual oil.

Within the limitations imposed by the data, the calculated infill target for each play is given in table 4. The total potential target for additional oil recovery using nontertiary techniques (in reservoirs where low permeability or oil gravity do not restrict production) is 19.9 billion barrels, or nearly 20 percent of the total OOIP. Extrapolation to all Texas oil reservoirs yields nearly 30 billion barrels of target oil (Fisher and Galloway, 1983). The validity of the calculated percentage is indirectly substantiated by results of a comparison of OOIP calculated by volumetric and by mass-balance methods in the Fullerton field, a major San Andres producer (George and Stiles, 1978). Using the same data base, the volumetric calculation was higher, suggesting that only 75 percent of the OOIP has actually been contacted

Table 4. Calculated volumes of oil that constitute the target for additional recovery from the major oil plays in Texas. Play number indicates location of play in figure 1. The piercement-salt-domes play (number 7) is not included because of insufficient data.

Play		OOIP (million bbl)	Estimated ultimate recovery (million bbl)	Unrecovered oil (%)	Residual oil saturation (%)	Water saturation (%)	Target oil* (million bbl)
1.	Eocene deltaic sandstone	243	93	62	13	28	49
2.	Yegua deep-seated salt domes	1,727	980	43	19	24	311
3.	Yegua salt-dome flanks	54	29	47	24	23	9
4.	Cap rock	---	---	No data	---	---	---
5.	Frio deep-seated salt domes	4,491	2,590	42	17	26	855
6.	Frio (Buna) barrier/strandplain sandstone	102	75	26	14	35	6
8.	Frio barrier/strandplain sandstone	4,222	2,235	47	25	26	560
9.	Wilcox fluvial/deltaic sandstone	182	89	51	29	29	19
10.	Jackson-Yegua barrier/strandplain sandstone	1,132	427	62	27	33	249
11.	Frio fluvial/deltaic sandstone (Vicksburg fault zone)	779	373	52	35	27	31
12.	San Miguel - Olmos deltaic sandstone	840	178	79	30	48	177
13.	Edwards restricted-platform carbonate	1,181	358	70	29	31	327
14.	Austin-Buda fractured chalk	---	---	---	37	34	---
15.	Glen Rose carbonate (stratigraphic/structural traps)	531	233	56	27	29	96
16.	Paluxy fault line	860	331	62	28	14	249
17.	Cretaceous sandstone (salt-related structures)	579	258	55	32	22	96
18.	Glen Rose carbonate (salt-related structures)	467	232	50	32	27	30
19.	East Texas Woodbine sandstone	8,126	6,536	20	15	14	173
20.	Woodbine fluvial/deltaic/strandplain sandstone	2,291	1,584	31	21	12	160
21.	Woodbine fault line	559	267	52	15	10	199
22.	Strawn sandstone	992	357	64	28	30	238
23.	Bend Conglomerate†	241	99	59	24	30	60
24.	Caddo reef	701	206	71	27	27	238
25.	Upper Pennsylvanian shelf sandstone	233	72	70	28	29	72
26.	Pennsylvanian reef/bank	924	405	56	37	23	74
27.	Upper Pennsylvanian slope sandstone	513	108	79	32	38	138
28.	Eastern Shelf Permian carbonate	3,005	878	71	31	33	932
29.	Horseshoe Atoll	4,691	2,412	49	28	25	563
30.	Spraberry-Dean sandstone	10,581	660	93	34	36	4,232**
31.	Central Basin Platform unconformity	1,342	354	74	26	30	498
32.	Ellenburger fractured dolomite	3,150	1,270	60	29	20	756

Table 4. (Cont.)

Play	OOIP (million bbl)	Estimated ultimate recovery (million bbl)	Unrecovered oil (%)	Residual oil saturation (%)	Water saturation (%)	Target oil* (million bbl)
33. Silurian-Devonian ramp carbonate	739	322	56	32	25	96
34. Silurian-Devonian ramp carbonate (South Central Basin Platform)	561	275	51	27	39	39
35. Silurian-Devonian ramp carbonate (North Central Basin Platform)	698	201	71	30	24	223
36. Yates area	4,070	2,040	50	25	26	692
37. San Andres - Grayburg carbonate (Ozona Arch)	837	230	73	25	24	452
38. San Andres - Grayburg carbonate (South Central Basin Platform)	10,286	2,712	74	25	25	4,217
39. San Andres - Grayburg carbonate (North Central Basin Platform)	2,400	818	66	26	19	816
40. Permian sandstone and carbonate	2,961	1,053	64	32	37	385
41. Clear Fork platform carbonate	4,084	924	77	30	28	1,429
42. Queen platform/strandplain sandstone	324	103	68	26	37	87
43. Wolfcamp platform carbonate	388	125	68	32	25	97
44. Pennsylvanian platform carbonate	442	101	76	35	28	119
45. Northern Shelf Permian carbonate	12,021	4,209	65	40	23	1,562
46. Delaware sandstone	484	92	81	19	41	237
47. Panhandle granite wash/ dolomite	6,060	1,450	76	35	37	1,212
48. Panhandle Morrow sandstone	188	53	72	27	33	60
Total	101,282	38,397				19,938

*Target oil = [percent unrecovered - (ROS/1-Sw)] x OOIP. ROS = residual oil saturation; Sw = water saturation; OOIP = original oil in place.

†Ranger field removed from calculation because of inadequate data.

**Total should be significantly reduced because of low permeability and fractured nature of most reservoirs; only one fourth, or 1,050 million barrels, was included in final summation of target.

by producing wells and was thus reflected in the mass-balance calculation. In other words, 25 percent of the OOIP remained as a target for infill development (George and Stiles, 1978).

Recovery efficiencies of plays in North-Central and West Texas and the Texas Panhandle are decidedly lower than are those of Coastal Plain and East Texas plays. Consequently, targets for additional oil recovery abound in the Paleozoic province north and west of the Marathon-Ouachita structural front (fig. 14). Principal targets are concentrated on the Central

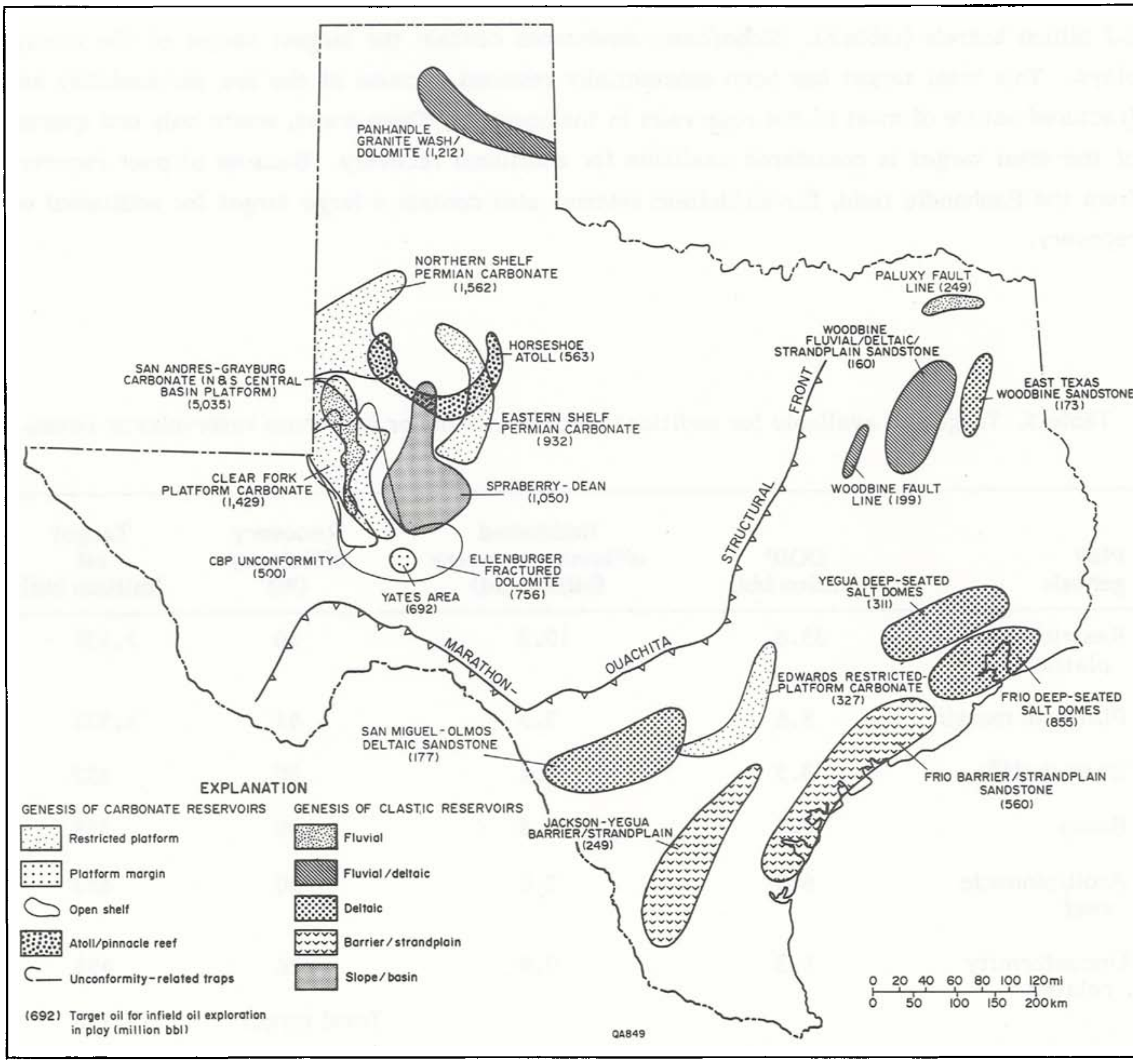


Figure 14. Geographic distribution of target oil potentially available for additional recovery from major Texas reservoirs. North of the Marathon-Ouachita structural front, only those plays having more than 500 million barrels of target oil are shown; those shown to the south of the divide have a cutoff of 100 million barrels of target oil. Most of the target oil remains in Paleozoic carbonates of the Permian Basin.

Basin Platform and on the northern and eastern shelves of the Permian Basin. In far northern Texas, the Panhandle granite-wash/dolomite play alone has a target in excess of 1 billion barrels. Targets for additional oil recovery in the Gulf Coast province are substantially smaller; the Frio deep-seated salt-domes and barrier/strandplain sandstone plays contain the largest targets for additional recovery (fig. 14).

Restricted-platform deposits contain almost 10 billion barrels of target oil (table 5), or 72 percent of the oil potentially available for additional recovery from carbonates (fig. 15). The total target in carbonates is more than twice that contained in clastics, which amounts to 6.2 billion barrels (table 6). Slope/basin sandstones contain the largest target of the clastic plays. This total target has been substantially reduced because of the low permeability and fractured nature of most of the reservoirs in the Spraberry-Dean trend, where only one quarter of the total target is considered available for additional recovery. Because of poor recovery from the Panhandle field, fluvial/deltaic systems also contain a large target for additional oil recovery.

Table 5. Target oil available for additional recovery in major carbonate reservoirs in Texas.

Play genesis	**OOIP (billion bbl)**	**Estimated ultimate recovery (billion bbl)**	**Recovery efficiency (%)**	**Target oil (million bbl)**
Restricted platform	33.6	10.2	30	9,837
Platform margin	8.6	3.5	41	1,531
Open shelf*	3.5	1.4	40	852
Ramp	2.0	0.8	40	358
Atoll/pinnacle reef	6.0	3.0	50	652
Unconformity related	1.3	0.4	26	498
			Total target	13,728

*Austin-Buda fractured-chalk play not included in the summation because of insufficient data.

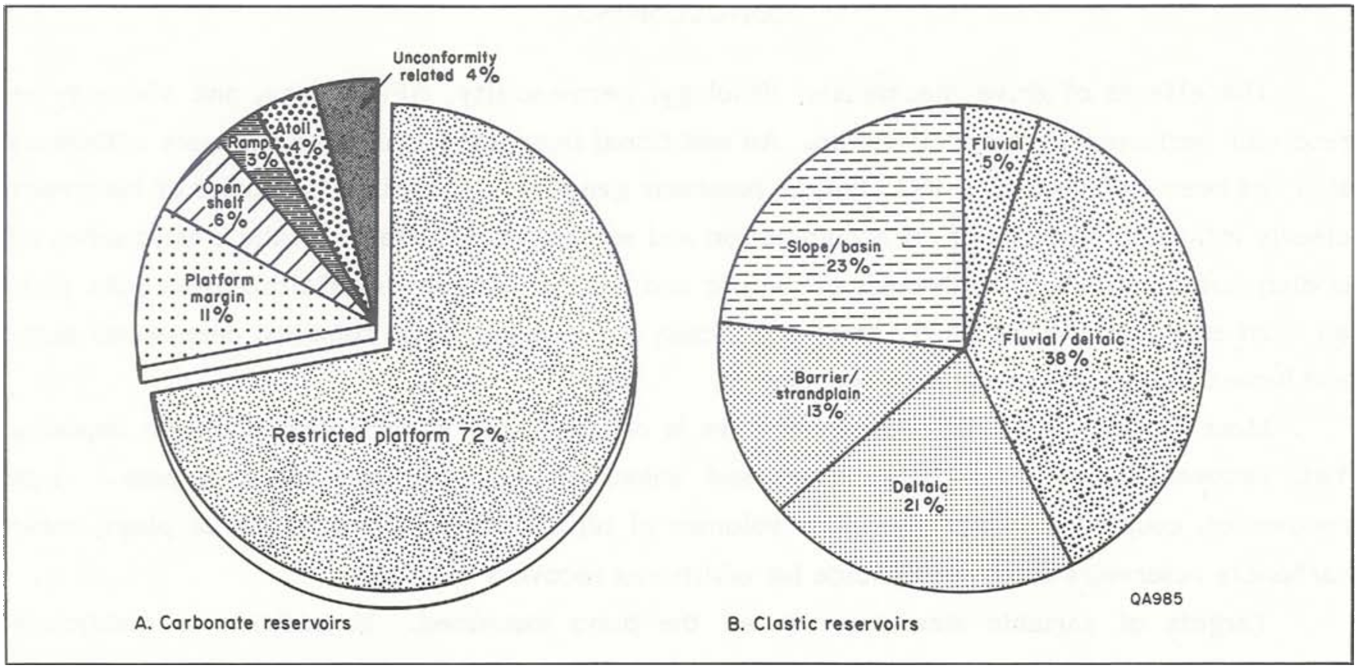


Figure 15. Distribution of target oil in (A) carbonate reservoirs and (B) clastic reservoirs.

Table 6. Target oil available for additional recovery in major clastic reservoirs in Texas.

Play genesis	OOIP (billion bbl)	Estimated ultimate recovery (billion bbl)	Recovery efficiency (%)	Target oil (million bbl)
Fluvial	1.5	0.6	40	328
Fluvial/deltaic	13.2	5.4	40	2,319
Deltaic	13.9	9.5	68	1,323
Barrier/ strandplain	5.8	2.8	49	815
Slope/basin	11.6	0.9	8	1425 (4607*)
			Total target	6,210

*Only 25 percent of target oil was included in the calculation because the reservoir sandstones are tight and fractured.

CONCLUSIONS

The effects of drive mechanism, lithology, permeability, API gravity, and viscosity on reservoir performance are well known. An additional important control on recovery efficiency that has been emphasized in this study is reservoir genesis. Depositional histories of reservoirs clearly influence patterns of oil accumulation and subsequent recovery. In the clastic suite, oil is distributed fairly evenly throughout paralic and basinal sandstones. Deltaic reservoirs yield oil most efficiently, whereas the stratigraphically and diagenetically complex, deep-water slope and basinal sandstones are poor producers.

Most of the oil in carbonate reservoirs is concentrated in restricted-platform deposits. Yet, recovery from these dolomitized and anhydrite-cemented reservoirs is poor. Low recoveries, coupled with the enormous volumes of oil contained in this group of plays, make carbonate reservoirs an obvious choice for additional recovery strategies.

Targets of variable size occur in all the plays examined. In addition to restricted-platform carbonates and slope/basin sandstones, platform-margin carbonates, deltaic sandstones in the Houston salt basin, and barrier/strandplain sandstones offer the best potential for improved oil recovery.

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APPENDIX

Trap Styles in Gulf Coast Plays

Oil in major reservoirs in the Gulf Coast and East Texas Basins is trapped in structures of three broadly defined structural styles. Fault-bounded traps are less productive than are stratigraphic traps or salt-related structures (fig. 16). The fault-bounded and stratigraphic trap categories can be further divided into two subclasses: One is composed of simple fault-bounded structures in which the displaced block may be either upthrown or downthrown relative to the autochthonous block; faulting postdates deposition, and folding is commonly minor. Examples include the Woodbine and Paluxy fault-line plays of East Texas and the Edwards and Wilcox plays of Central Texas (fig. 16). The second subclass comprises complex fault-bounded structures in which the allochthonous block is downthrown along a basinward-dipping, concave fault plane. Syndepositional faulting and concomitant anticlinal folding of the downthrown sediments deform a thickened section into elongate, strike-parallel rollover anticlines, which constitute the trap. Frio plays along the central, southern, and, to a lesser degree, upper Texas Gulf Coast are examples. Trap styles merge and become less distinguishable where the Frio and Vicksburg fault zones enter the Houston salt-structure province.

Stratigraphic traps in the Gulf Coast Basin are diverse and range from classic unconformity-related traps, such as at the East Texas field, to the fractured chalks of the Austin-Buda play. Because the fractured zones in the Austin Chalk are strongly related to lithology, traps of this nature are considered partly stratigraphic in origin. Mud-encased, wave-dominated deltaic sand bodies occur locally as the trap mechanism in the San Miguel - Olmos deltaic sandstone play, as do unconformity-related structures.

The bar graph in figure 16 illustrates the relative importance of each of these trap styles. Grouping all of the OOIP in the stratigraphic trap plays (including fractured chalk) into a single category allows the emergence of stratigraphic traps as the dominant mechanism for the concentration of hydrocarbons on the Gulf Coast. Of almost equal importance are salt-related structures of the East Texas and Houston salt-structure provinces. About one third of the oil resource in the Gulf Coast Basin is contained in structures formed by the migration of salt into diapirs and domes and by the formation of salt-related turtle structures. In the East Texas salt-structure province, most oil is produced from deep salt-cored anticlines (76 percent). Production from turtle-structure anticlines is a distant second (22 percent), and piercement salt domes account for the remaining 2 percent of production (Wood and Giles, 1982).

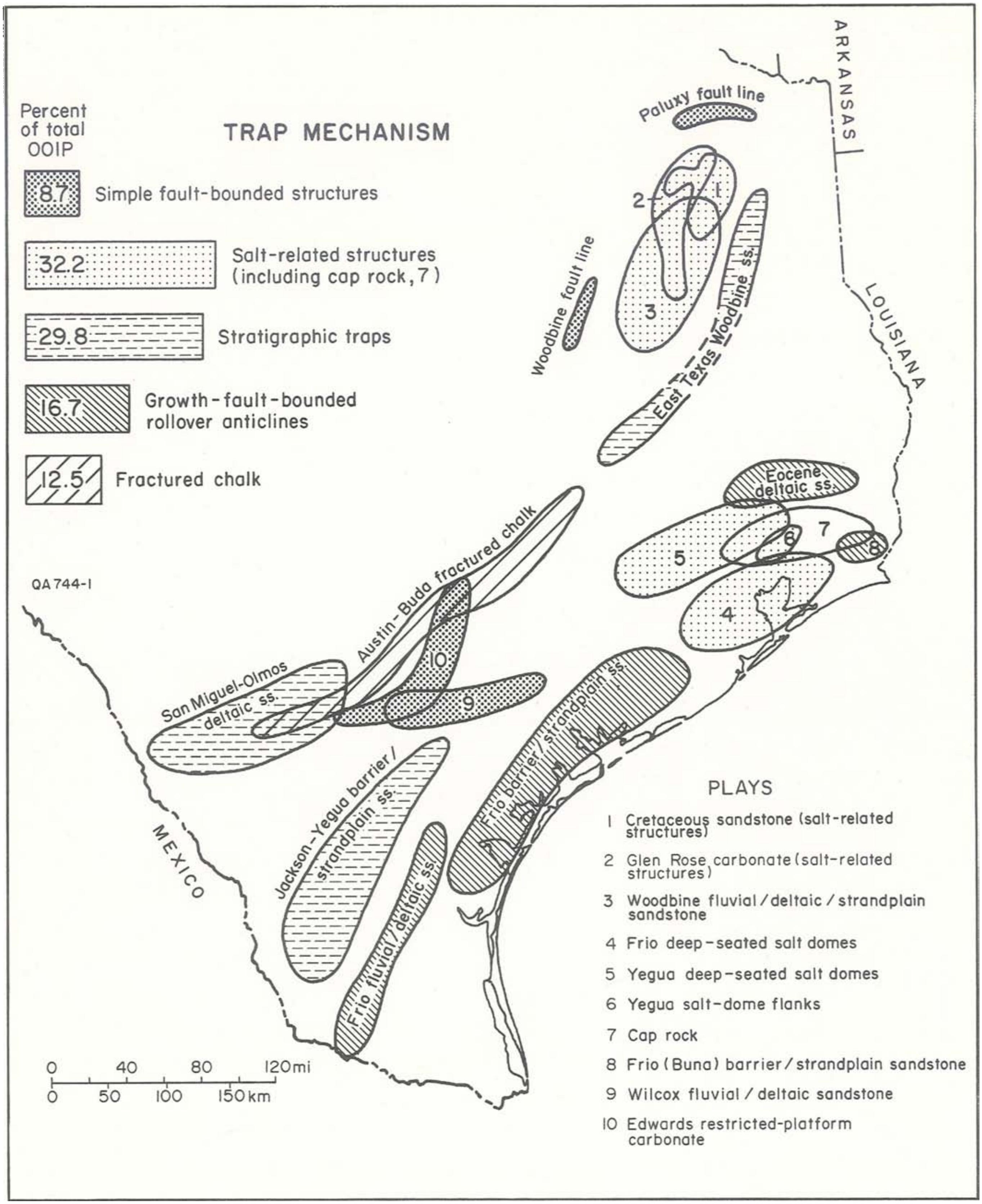

Figure 16. Dominant trapping mechanisms in the Cretaceous and Tertiary plays of the Texas Gulf Coast. Bar graphs represent the percentage of the total original in-place oil resource of this region that structures in each category contain.